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Energy Audit And Management Of Induction Motor Using Field Test And Genetic Algorithm

Nagendrappa. H[1] , Prakash Bure[2]
Department of Electrical & Electronics Engineering , National Institute of Technology Karnataka, Surathkal, INDIA
Email: nagendra_nitk@yahoo.com , prakash.bure@gmail.com

Abstract-**This paper proposes an economical method that can be used by industries/plants to make a right decision in replacing the inefficient induction motors with efficient ones. proposed method focuses on the field efficiency of motors without the needs for removing motors and measuring the output power. The use of a few sets of measured data from field test coupled with the genetic algorithms using one operating point for evaluating motor equivalent circuit parameters instead of using the no load and blocked-rotor tests is proposed. Test results indicate that this method has a high accuracy, then it is suitable for conducting onsite energy audit of motors in order to project cost savings and payback and to support a confidence decision regarding the investment in higher efficiency motors.**

Index Terms-**energy audit, field test, parameter estimation, induction motor**

I. INTRODUCTION

The majority of motors in the field are induction motors. There are many methods relevant to field efficiency evaluation in the literature and new methods are appearing every year [1]. As the cost of energy is growing at a high rate, the industries can save a considerable amount of money by replacing inefficient motors with new more energy-efficient ones[4]. In the past, many methods were used to calculate the efficiency of induction motors, one common method is to test the motor under load conditions and then monitor the input and output at different load points using a dynamometer and torque transducer. This is the most straightforward method to measure the output power directly from the shaft without any need to calculate losses. Conventionally, the shaft torque method offers the most accurate field efficiency evaluation method, however, this is not suitable for the field evaluation because this process involves the removal of motor from service to place it on a test stand and couple it to the dynamometer. It can be seen that this method is impractical and costly. Another accurate method for field efficiency evaluation relies on using the no-load and blocked-rotor test results to estimate the motor equivalent circuit parameters. The blocked-rotor test procedures require reduced voltage and frequency in addition to preventing the rotor from rotating which is a difficult task. Comparison of actual motor efficiencies is certainly a valid tool to justify the use of one motor over another motor.

In the field, one may estimate the efficiency based on information from the name plate and input measurements[1], such as the slip method(SM) and current method (CM).The slip method presumes that the per unit (p.u) of load is closely proportional to the P.u. of the ratio of measured slip to full-load slip and The current method presumes that the p.u. of load is also closely proportional to the p.u of the ratio of measured current to full-load current, and then the motor field efficiency can be estimated by using the following relationships.

$$\text{Load(p.u)} = \frac{N_{syn} - N_r}{N_{syn} - N_{fl}\,(V_{nameplate}/V_{meas})^2} \qquad (1)$$

$$\text{Load(p.u)} = \frac{I_{measured} \times V_{measured}}{I_{fl} \times V_{nameplate}} \qquad (2)$$

$$\text{Output power Pout} = \text{Prated (Nameplate) x Load (p.u)} \qquad (3)$$

$$\text{Field Efficiency} = \frac{\text{Pout}}{\text{Pin (Measured)}} \qquad (4)$$

Where N_{syn}, N_r and N_{fl} denote the synchronous speed, measured rotor speed and nameplate full-load speed of motor respectively, V_{meas} and $V_{nameplate}$ stand for the measured voltage and nameplate rated voltage respectively, Where $I_{measured}$ and I_{fl} denote the measured current and nameplate full-load current respectively, P_{rated} and P_{in} are the nameplate rated power and measured input power respectively. Using SM and CM methods, a few problems may occur. First the nameplate efficiencies of a given motor can be evaluated according to different standards. Second, the nameplate data are rounded. Third, the motor may have been rewound. Hence, the error in estimated efficiency could be very high.

II. GENETIC ALGORITHM

The genetic algorithm is another method which may be used to solve a system of nonlinear equations. The genetic algorithm uses objective function based on some performance criterion to calculate an error [5]. However, the genetic algorithm is based on natural selection using random numbers, and does not require a good initial estimate. That is, solutions to complex problems could evolve from poor initial estimates in a game of survival of the fittest. Genetic algorithms manipulate strings of binary digits, and measure each string's strength with a fitness value. The stronger strings advance, and mate with other strong strings to produce offspring. Eventually one string emerges as the best. One of the most important advantages of the genetic algorithm is that they are able to find the global minimum instead of a local minimum

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and that the initial estimate need not be close to the actual values. Another advantage is that they do not require the use of the derivative of the function, which is not always easily obtainable or may not even exist for example when dealing with real measurements involving noisy data.

A. *The Main Operators*

The mechanics of the genetic algorithm are elementary, involving nothing more than copying strings, random number generation, and swapping partial string. A simple genetic algorithm that produces good results in many practical problems is composed of three operators:

i. Reproduction
ii. Crossover
iii.Mutation

reproduction is a process in which individual strings are selected according to their fitness. The fitness is determined by calculating how well each string fits an objective function. Copying strings according to their fitness value implies that strings that fit the objective function well have a higher probability of contributing one or more offspring in the next generation. This process of reproduction is of course an artificial version of natural selection. Here the objective function is the final arbiter of the string-creature's life or death.

Stochastic sampling with replacement is the name given to a simple reproduction scheme. This scheme is based on placing the string probabilities on a weighted roulette wheel and spinning the wheel to select a string. The probabilities on the roulette wheel are determined by the string's fitness as a percentage of the total population fitness. The roulette wheel selection scheme utilizes random numbers to simulate a spin of the wheel. Once a string is selected by the reproduction operator, the string is copied into a mating pool and waits to be selected for further genetic operator action. The roulette wheel scheme does not guarantee that the fittest strings will be selected albeit their probability for selection is high. Therefore, this method may not produce the best results, especially for problems with small populations.

Crossover is a two step process that involves mating and swapping of partial strings. Each time the crossover operator takes action, two randomly selected strings from the mating pool are mated. Then, in the case of simple crossover, a position along one string is selected at random, and all binary digits following the position are swapped with the second string. The result is two entirely new strings that move on to the next generation. This can be more clearly understood by the following example in which string 1 and string 2 have already been chosen to mate as shown in Fig.1

Crossover point
String A 1 0 0 1 1 | 0 0 1

String B 1 0 1 0 1 | 1 1 0

String A' 1 0 0 1 1 1 1 0

String B' 1 0 1 0 1 0 0 1

Figure 1. The crossover operator

mutation follows crossover and protects against the loss of useful genetic information (1's and 0's). the operator works by randomly selecting one string and one bit location, and changing that strings bit from a 1 to a 0 or vice versa as shown in Fig. 2. The probability for mutation to occur is usually very small, roughly one mutation per thousand bit transfers.

bit selected
for mutation

String A 1 0 0 0 1 1 | 0

String A' 1 0 0 0 1 1 1

Figure 2. The mutation operator.

The three genetic operators, reproduction, crossover, and mutation, provide an effective search technique using natural selection and random number generation. Advanced operators, such as, dominance, inversion, and segregation exist, but are generally not essential for good results to many problems. In some cases the advanced operators can degrade the performance of the genetic algorithm.

III. FIELD EFFICIENCY ESTIMATION SET UP

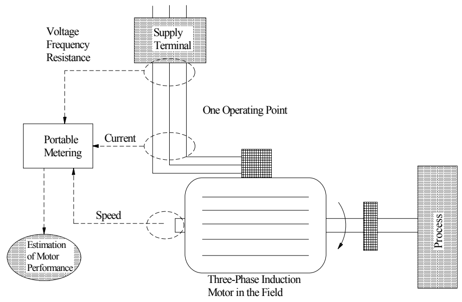

Figure 3. Implementation of the proposed method

The field efficiency evaluation is based on the equivalent circuit method. The motor parameters can be estimated by using a few sets of data from the field test and nameplate information coupled with the genetic algorithms instead of using the no-load and blocked-rotor test results [6]. The field test data which rely on measuring the input voltage, current, electrical power, stator resistance and output speed of the motor are obtained from the measured values at either one operating point test (OPT) or two operating points test(TPT) which need not be close to no-load or full-load values as shown in Fig. 3

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IV. EQUIVALENT CIRCUIT

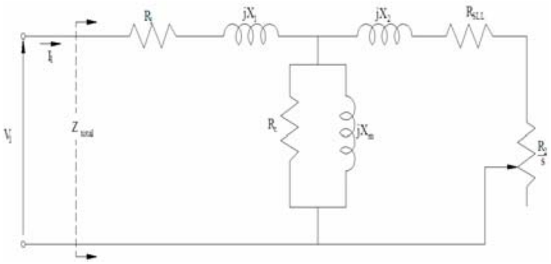

Figure 4. Equivalent circuit diagram of 3-phase induction motor.

Most models which were used in the past eliminated the stray load loss. Neglecting this loss introduces a significant error in estimating the efficiency. The stray load loss will decrease with decreasing output power proportional to the square of the torque. It is worth mentioning that this proposed model includes the stray load loss parameter R_{SLL} as shown in Fig.4. The parameter R_{SLL} can be expressed as

$$R_{SLL} = \frac{M(1 - S_f) R_2}{S_f}$$

where, M = per unit full-load power, which is set to be the value (0.002<M<0.0189) [6] or 1.8% of the full load, R_{sLL} = stray load loss, S_f = full load slip.

Efficiency assessed through an equivalent circuit method is based on the impedance values of an equivalent circuit, shown in Fig. 4. The six impedances are stator resistance R_1, stator leakage reactance X_1, magnetizing reactance X_m, core-loss resistance R_C, rotor leakage reactance X_2, and rotor resistance R_2. The slip affects the load of the equivalent circuit.

$$I_{1i,cal} = \frac{V}{Ztotal} \quad \text{Amps} \tag{5}$$

$$P_{in.cal} = 3 V_1 I_1 PF \quad \text{Watts} \tag{6}$$

Where, V_1 and I_1 are rms values of the input phase voltage and current respectively, and PF is the power factor.

The advantage of the equivalent circuit method is that the performance of a motor can be predicted at any load when the impedance values are known. On the other hand, the impedance values can change a great deal when the motor speed varies between standstill and no load, due to deep bar effects and magnetic saturation. There are different approaches for obtaining the impedance values.

When the six-impedance equivalent circuit is used, all the losses other than the friction and wind age loss that are not represented by the stator copper, rotor copper, and no-load core-loss resistances, are grouped together in a collective loss named stray-load loss.

V. PARAMETER ESTIMATION FROM FIELD TEST

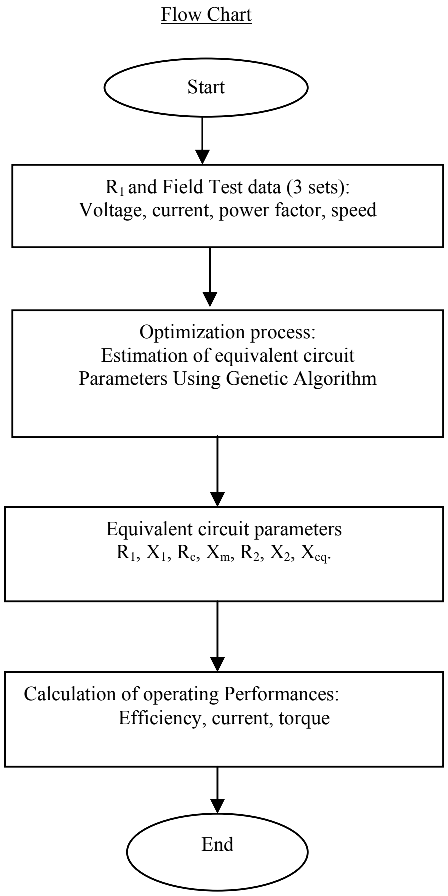
Flow Chart
Start
R1 and Field Test data (3 sets):
Voltage, current, power factor, speed
Optimization process:
Estimation of equivalent circuit
Parameters Using Genetic Algorithm
Equivalent circuit parameters
R1, X1, Rc, Xm, R2, X2, Xeq.
Calculation of operating Performances:
Efficiency, current, torque
End

Figure 5. Flow chart of proposed technique

The equivalent circuit parameters can be estimated by using the field test data coupled with genetic algorithm. The flow chart of the proposed technique is shown in Fig.5.The technique for estimating the equivalent circuit parameters proceeds as follows [1]. From the field test of motor (on-site), only 3 sets of data of motor input voltage, current, power factor and speed, which need not be close to no-load or full-load values, are directly measured while the motor is in service. The stator winding resistance R_1 which is obtained from resistance measurements is also included. However, it remains inconvenient to measure the shaft torque in the field.

For this reason, the motor input power data is then proposed in this technique. Then these test data sets are determined in the optimization process. The aim of genetic algorithm (binary or floating pint implementation) is to minimize the error of (7), or maximize the fitness of (8). After optimization process, the parameters of equivalent circuit can be obtained and finally, the operating performances of an actual induction motor can be predicated.

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$$F_{objective} = \sum_{i=1}^{n}\left[\frac{Pin,cal}{Pin,data} - 1\right]^2 + \sum_{i=1}^{n}\left[\frac{I1i,cal}{I1i,data} - 1\right]^2 \quad (7)$$

$$Fitness = \frac{1}{1 + Fobjective} \quad (8)$$

Where I_1i, cal and Pin, cal are the calculated values using (5) and (6) respectively, $I_{1i,data}$ and Pin $_{,data}$ are the measured values obtained from the field test when n = 1 for the (OPT).

VI. RESULTS AND DISCUSSION

The proposed technique described in the preceding section is applied to three phase induction motor having the following motor ratings:

5hp (3.7kw), 380/400V, 7.9A, 50hz, 4-pole, 1420rpm. The optimization process results of estimated equivalent circuit parameters of motor obtained from the proposed technique. The results show that binary point implementation can be used in the genetic algorithm. Only one drawback of using the binary implementation is time consumption. Noting that the accurate value of Rc and Xm will be obtained if a set of data at light load is provided.

Equivalent circuit parameters: R1 = 2.6342Ω, R2 = 1.4535Ω, rc = 473.4942 Ω xm = 67.5317 Ω, X1 = 2.1256Ω, X2 = 2.1480 Ω.

From table-1, At one-quarter load, the measured efficiencies obtained from IEEE 112 Method B evaluation is 90 %, while the estimated efficiencies obtained from the OPT is 87.3 %. At full-load, the measured efficiency is 84 %, while the estimated efficiencies are 81 %. It can be observed that the accuracy of estimation is lower at full-load than at one-quarter load. Note that the synchronous speed is 1500 RPM while the speed at one-quarter load is 1485 RPM and at full-load is 1440 RPM. This can be attributed to the fact that at lower load the slip becomes smaller. Therefore, any small error in measuring speed will result in a significant error in slip.

Table I

Methods	Motor load			
	25%	50%	75%	100%
CM	96	94	90	85
SM	70	77	71	69
OPT	87.3	85	83.5	81
IEEE	90	88	86	84

Summary of Results of Estimated Efficiency for 5hp Motor at Various Loads Using OPT.

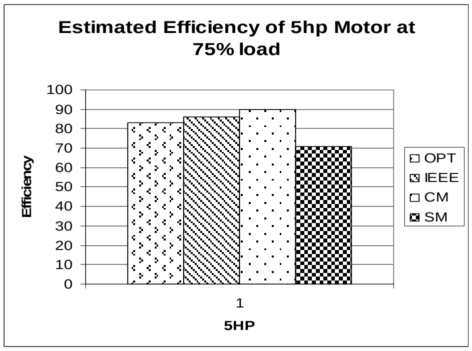

Figure 6. Estimated efficiency at 75% Motor load Using OPT compared with IEEE Std-112, CM and SM.

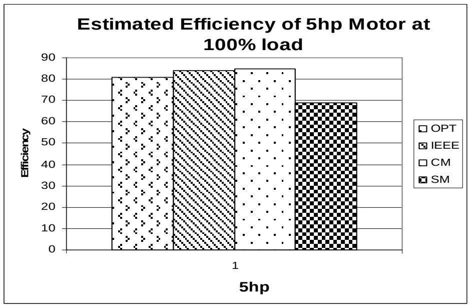

Figure 7. Estimated efficiency at 100% motor load using OPT compared with IEEE Std-112, CM and SM

The estimated efficiency results using the OPT at various loads of the 5hp motor at 2/4,3/4 and 4/4 load compared with those obtained from IEEE 112 Method B evaluation, current method (CM) and slip method (SM)are also illustrated in Fig.6 and Fig.7 respectively.

As mentioned in effective field efficiency estimation, the stray load loss was not ignored in this analysis; as a result the accurate estimated value of motor efficiency can be obtained. It can be observed that the efficiency values using CM and SM methods in Fig.6 and Fig.7 can lead to dramatic error in the estimation. This can be attributed to the fact that any small error in measuring current or speed will result in a significant error. It is recommended when using these methods that the current and speed are measured as accurately as possible.

VII. COST SAVING AND PAYBACK

The accurate field efficiency estimation using this proposed method can be used to determine the economics of investing in buying new energy-efficient motors. The Simple Payback method is the most popular technique to estimate how many years it will take to recover the cost of investment for higher efficiency motors. First, the annual cost savings (A_{saving}) in units is determined using the following formula [9]:

$$A_{Saving} = P_{out}\; L\; h_r\; C\left[\frac{1}{E_{ex}} - \frac{1}{E_{ee}}\right] \quad (9)$$

Where,

P_{out} : is the motor rated in KW,

L : is the percentage of full load divided by 100,

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h_r : is the annual operating hours,
c : Are the average costs (units/kwh),
E_{ex} : stand for the existing motor efficiency,
E_{ee} : the energy-efficient motor

Thus, it is suggested that the Present worth Life Cycle method [9] should be used. This technique relies on calculating the present value of the achieved savings taking into account the cost of capital and the inflation rate for energy cost. Once the effective interest rate (i), the expected annual rate of energy cost inflation (r_1), the required internal rate of return on investments (r_2) and the expected operating lifetime of the motor (n) values are defined, the following equations can be used to determine the feasibility of the investment.

$$i = \frac{100 + r_2}{100 + r_1} - 1 \qquad (10)$$

$$PW_{saving} = A_{saving} \times \frac{(1+i)^n - 1}{i(1+i)^n} \qquad (11)$$

Where PW $_{saving}$ denotes present worth of savings which can then be used to make the decision regarding the various alternatives available.

In order to quick estimate the payback period for the economics of investment, the cost of new energy-efficient motor can be simply divided by the annual savings to get the payback period. The estimated payback period can vary from 7 years up to 9 years depending on the operating load, the hours of operation and the cost per kilowatt-hour. It is important to mention that the efficiency figure used must be the efficiency value at the actual load point (3/4 load or full-load) since the fact that the efficiency of motor can vary significantly across the load [10].

$$\text{Pay Back Period(Years)} = \frac{\text{Cost of New Efficient Motor}}{\text{Annual Savings}} \qquad (12)$$

CONCLUSION

The proposed method for estimating efficiency of induction motor in the field has been described. This method relies on the on-site measurement of the input voltage, current, power and actual motor shaft speed without conducting no-load and blocked-rotor tests. The important advantages of this proposed technique over other methods are that it is a simple procedure; therefore it is possible to estimate the efficiency of motor in a short time while the motor is in service without the removal of motor, and that such procedure is inexpensive. It is worth noting that this proposed method is suitable for conducting on-site energy audits and management of actual motors. It provides information for the decisions to immediately replace motors with more efficient ones and it also provides the data base of in-service motors performance such as the future motor replacement decisions, the detection of under loading or over loading. This information can then be used to project cost savings and payback which are used to guide the decisions regarding the investment in efficient motors.

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